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(54) **SHOCK WAVE BARRIER USING MULTIDIMENSIONAL PERIODIC STRUCTURES**

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(21) Appl. No.: **13/093,602**

(22) Filed: **Apr. 25, 2011**

Related U.S. Application Data

(63) Continuation-in-part of application No. 12/473,275, filed on May 28, 2009, now Pat. No. 8,082,844.

(51) **Int. Cl.**
F41H 5/24 (2006.01)

(52) **U.S. Cl.**
USPC **89/36.01**; 89/920

(58) **Field of Classification Search**
USPC 89/36.01, 36.04, 36.11, 36.02; 109/49.5; 102/303; 52/506.1, 1
See application file for complete search history.

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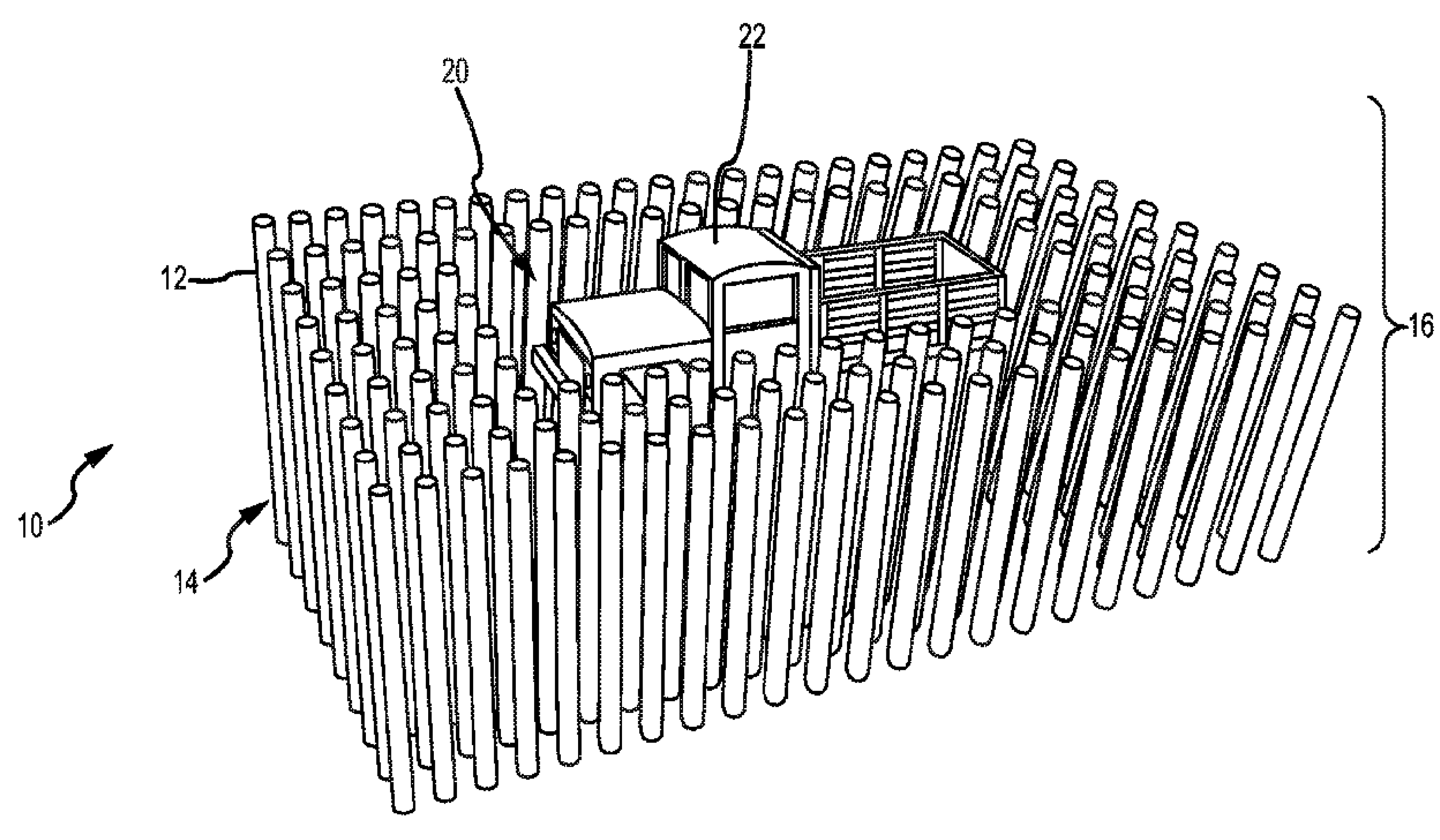
(57) **ABSTRACT**

A shock wave barrier comprises a periodic structure having the proper symmetry and local contrast modulation of the acoustic index to divert an incident shock wave by using constructive/destructive interference phenomena that produce a "band gap" in the transmission spectrum of the periodic structure. In general, shock wave energy within the band gap is reflected from the structure. Defect cavities may be formed in the periodic structure to create transmission resonances or "windows" in the band gap. A portion of the incident energy passes through the window and is concentrated in the defect cavities where it is dissipated by other means. The band gap can be quite wide, at least 50% of the center wavelength, and thus can provide an effective barrier from a wide variety of threats with varying blast pressure and range. The structure may be periodic in two or three dimensions providing a band gap barrier in two or three dimensions, respectively.

20 Claims, 13 Drawing Sheets



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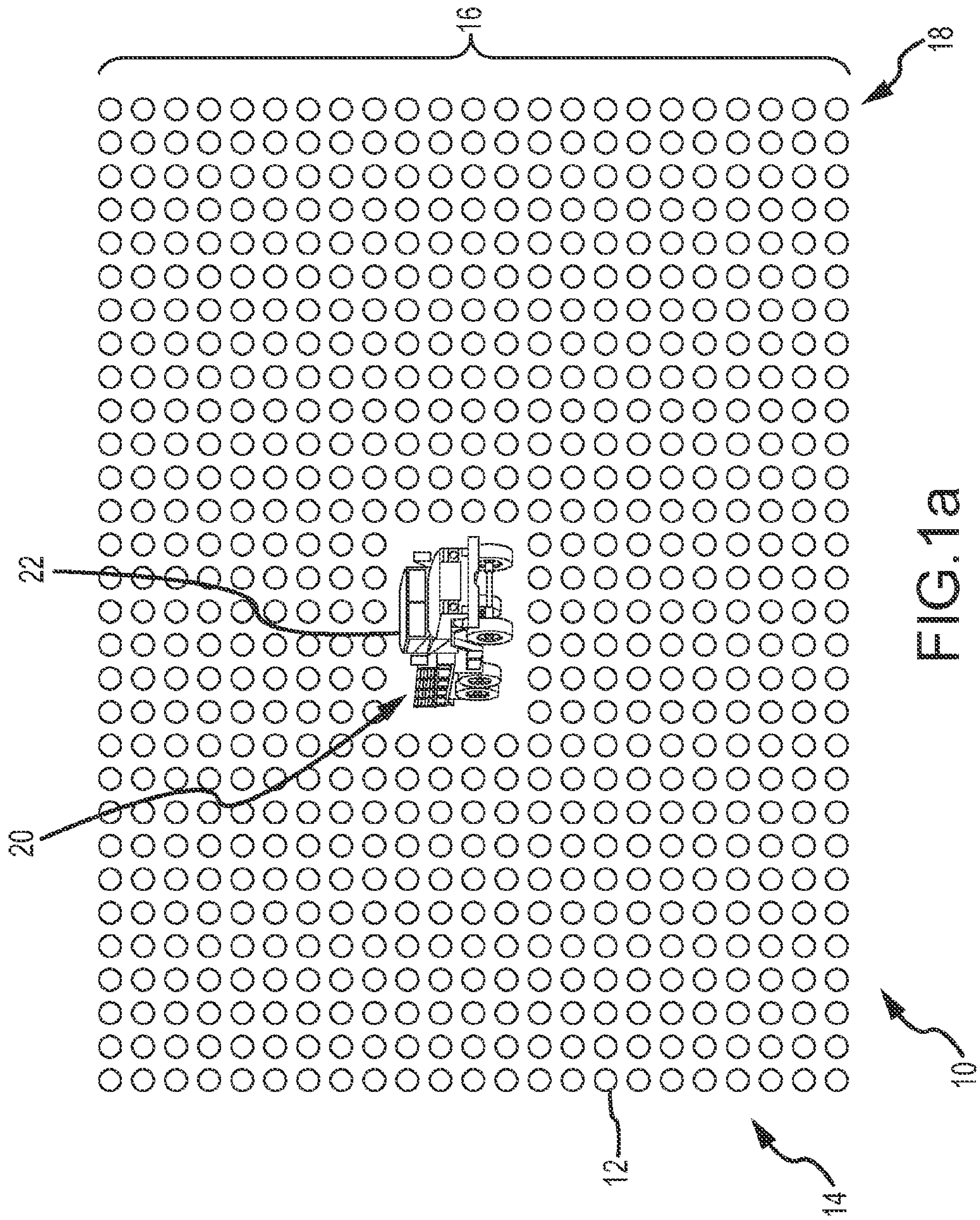


FIG. 1a

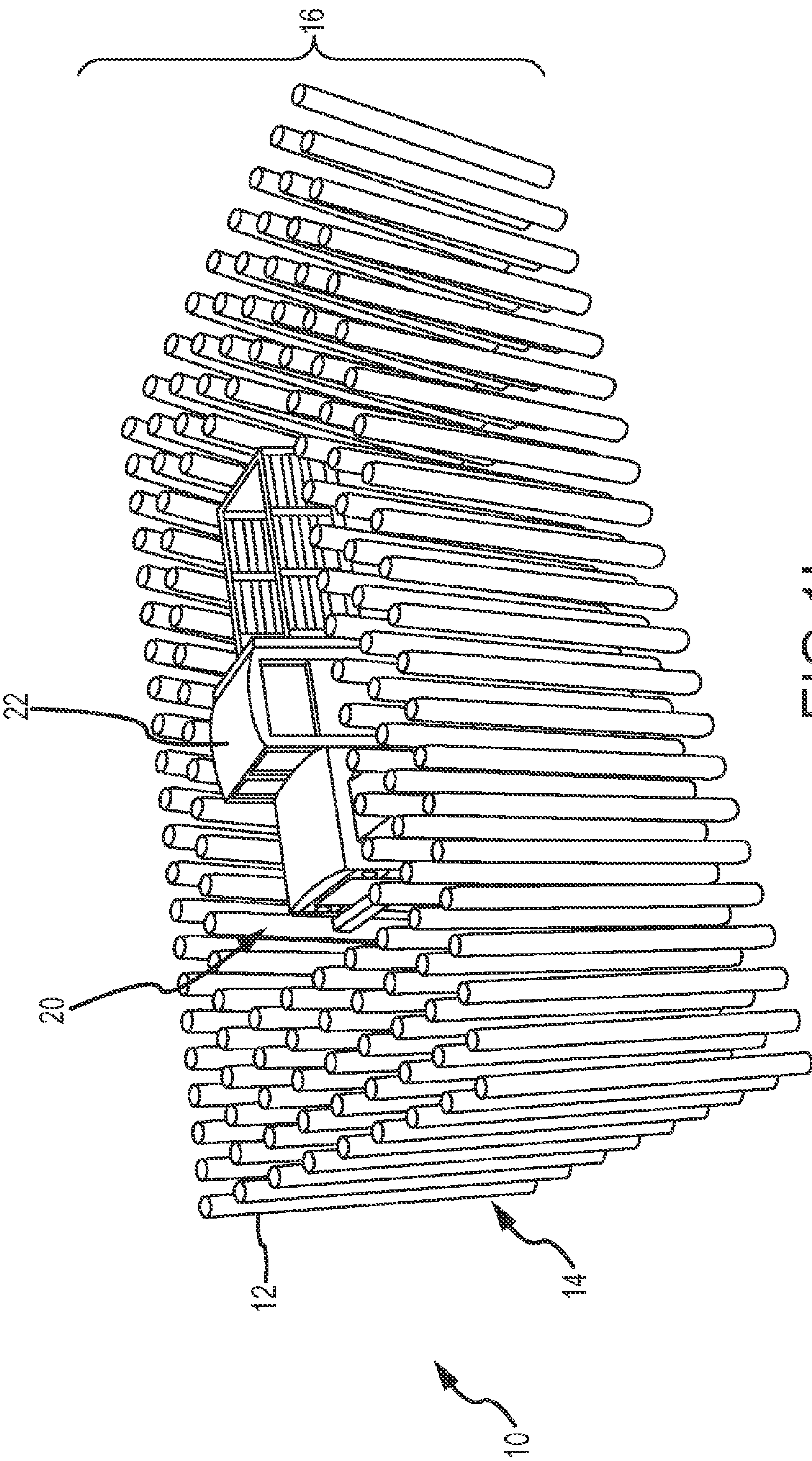
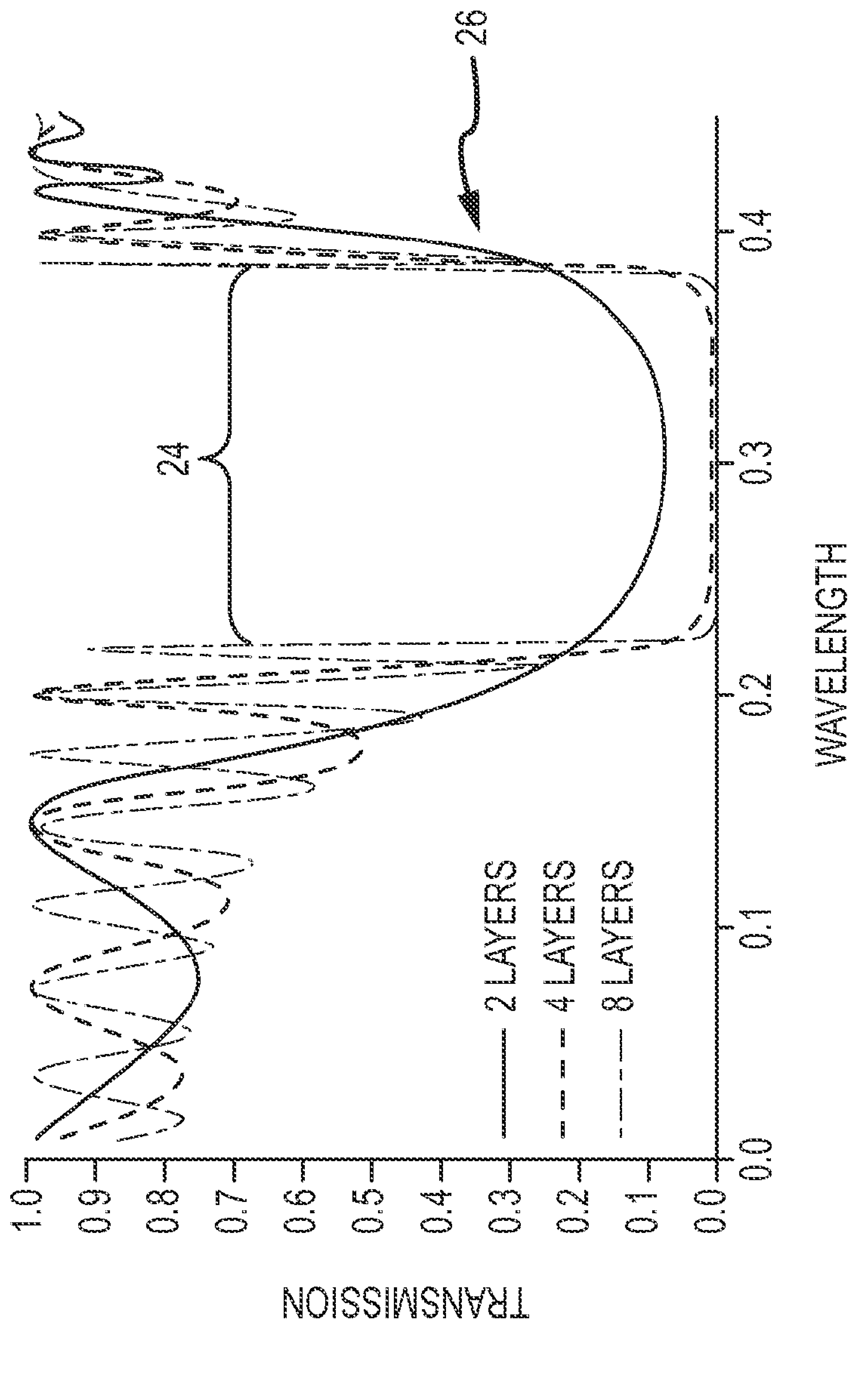


FIG.1b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26

FIG.2

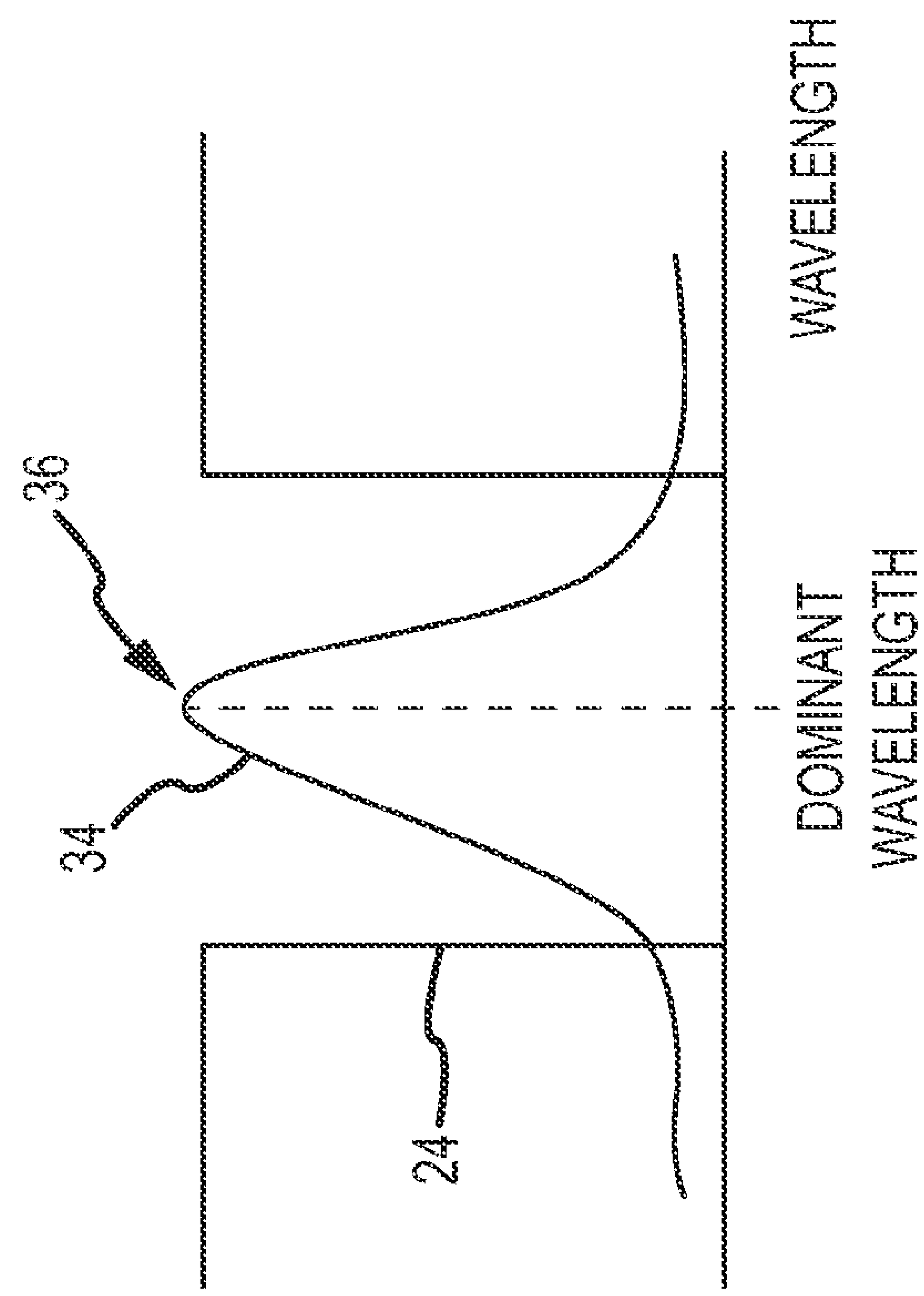

FIG.3b

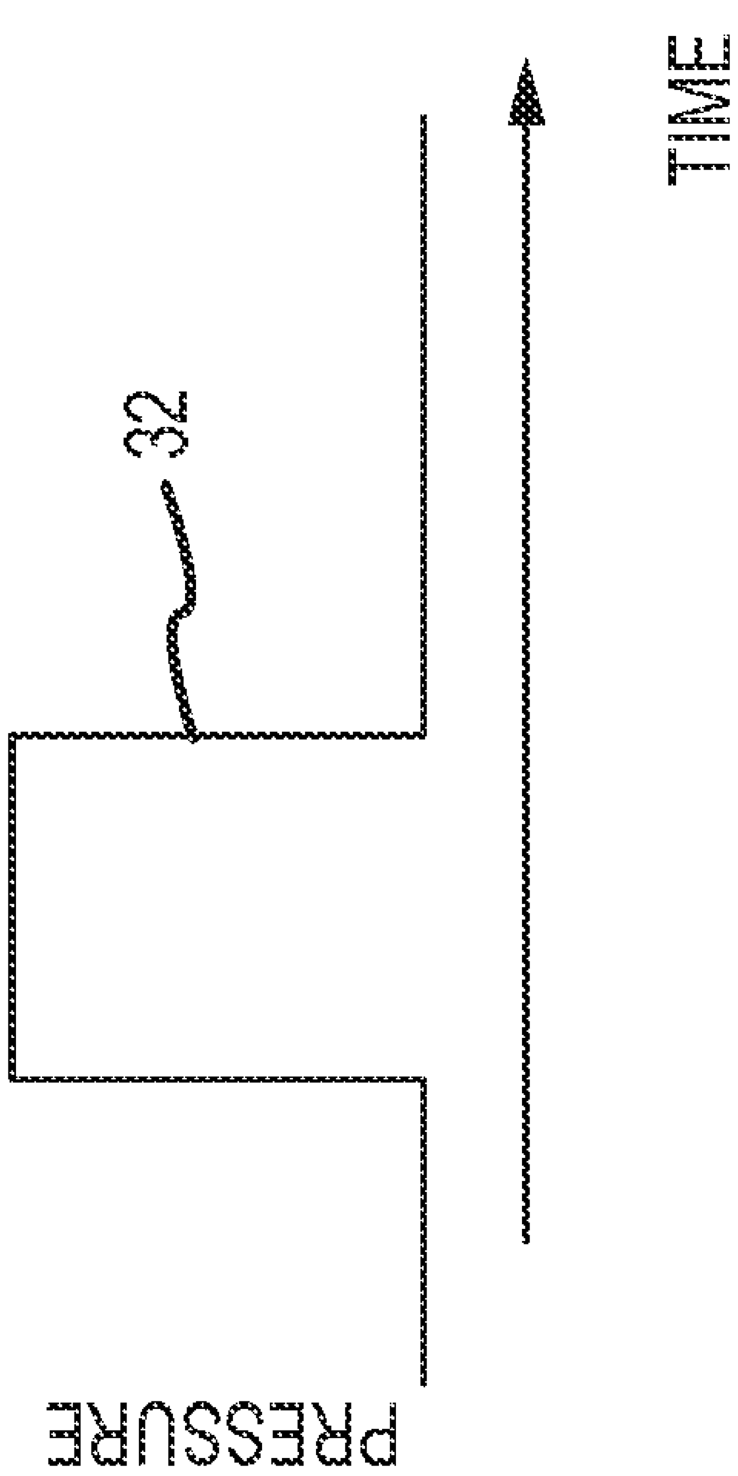

FIG.3a

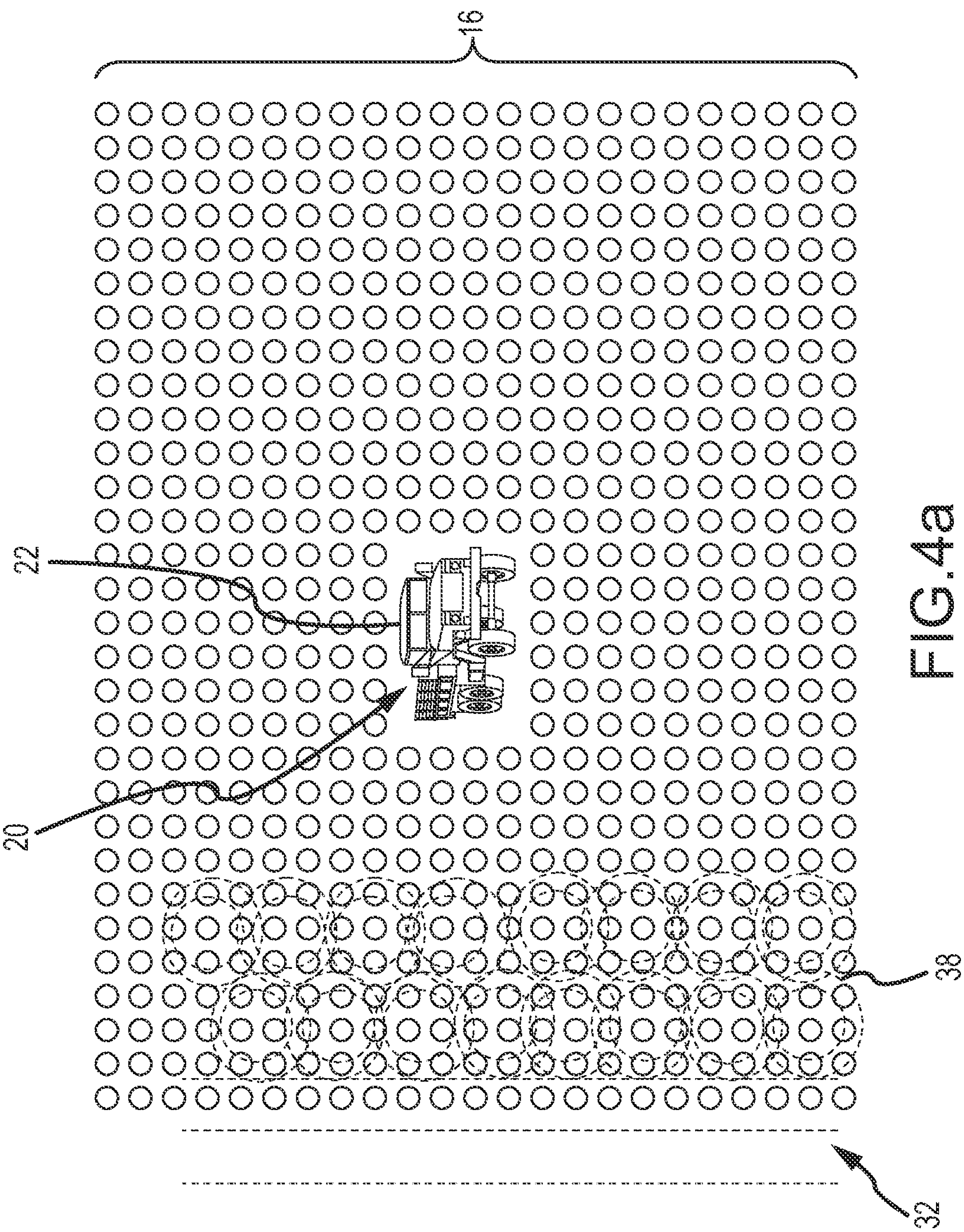

FIG. 4a

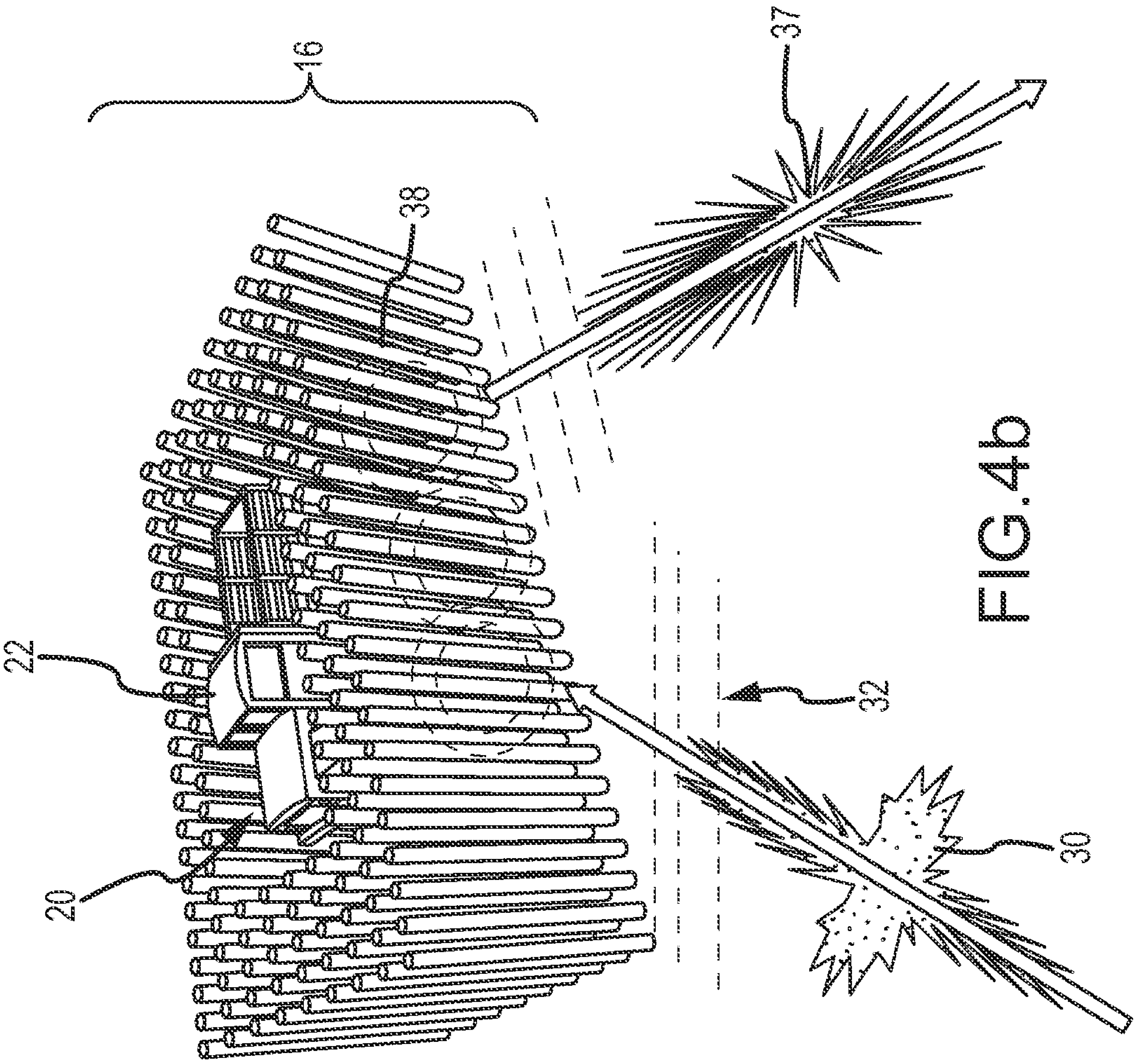

FIG.4b

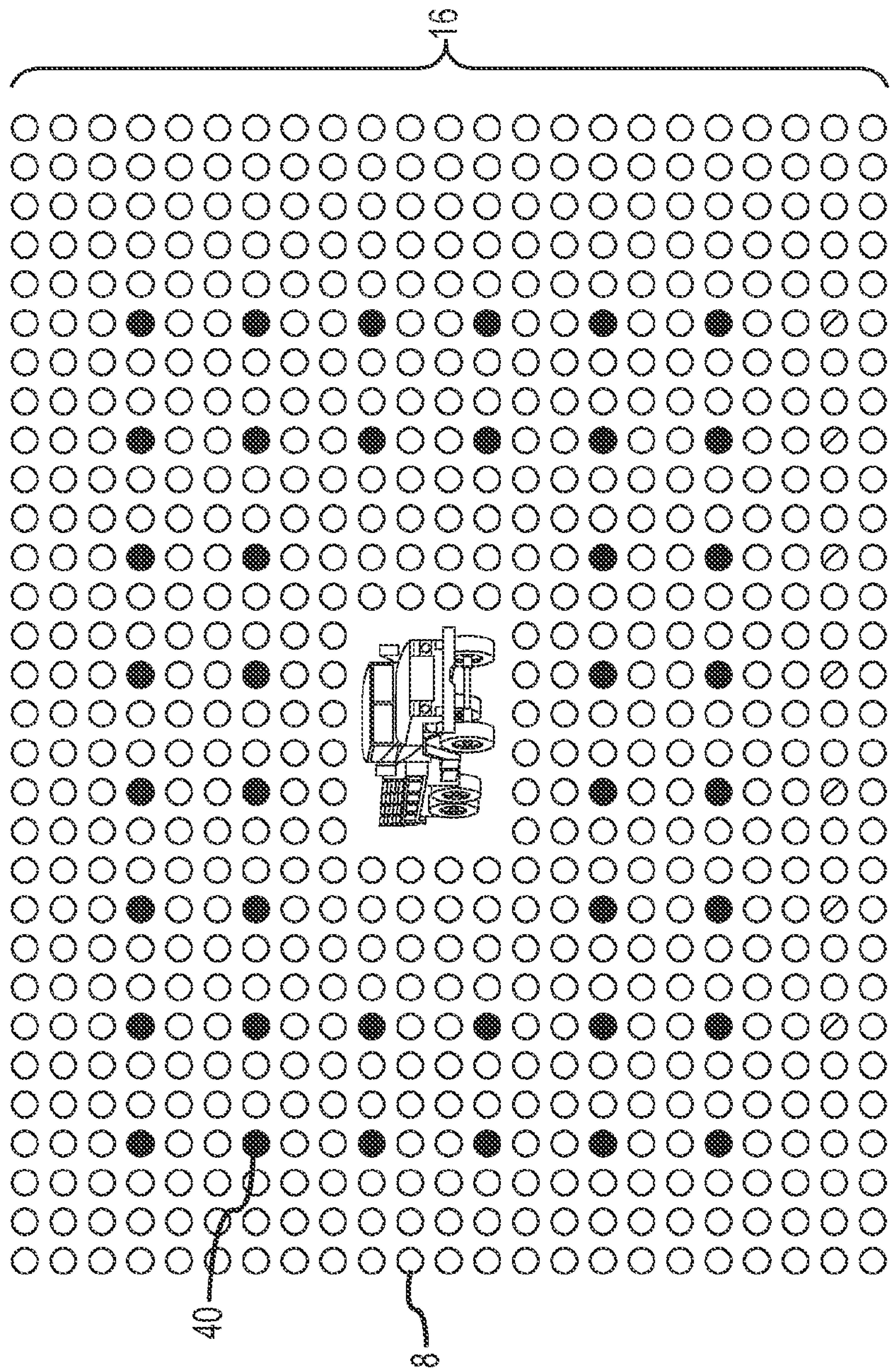

FIG.5

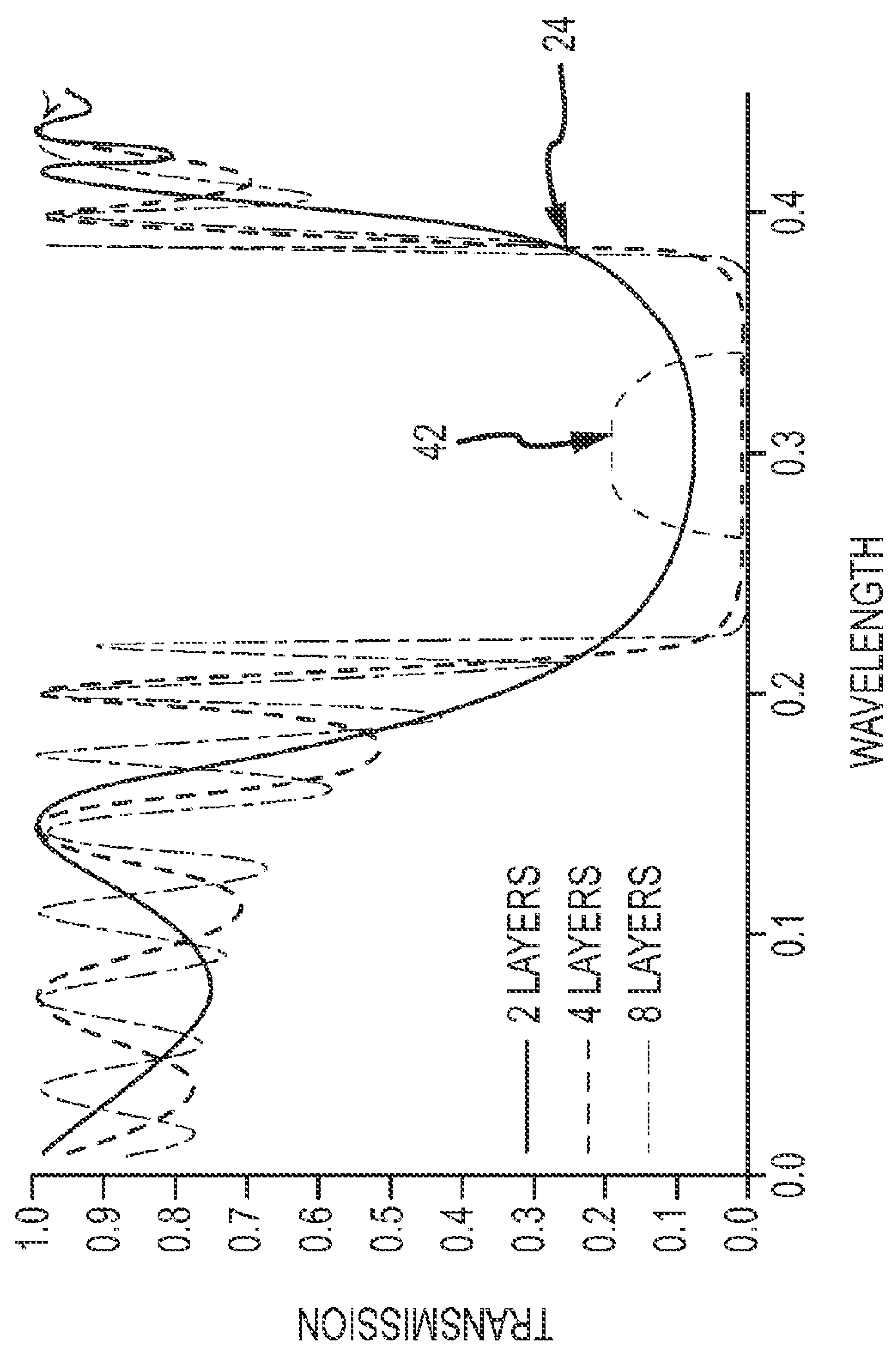
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FIG.6

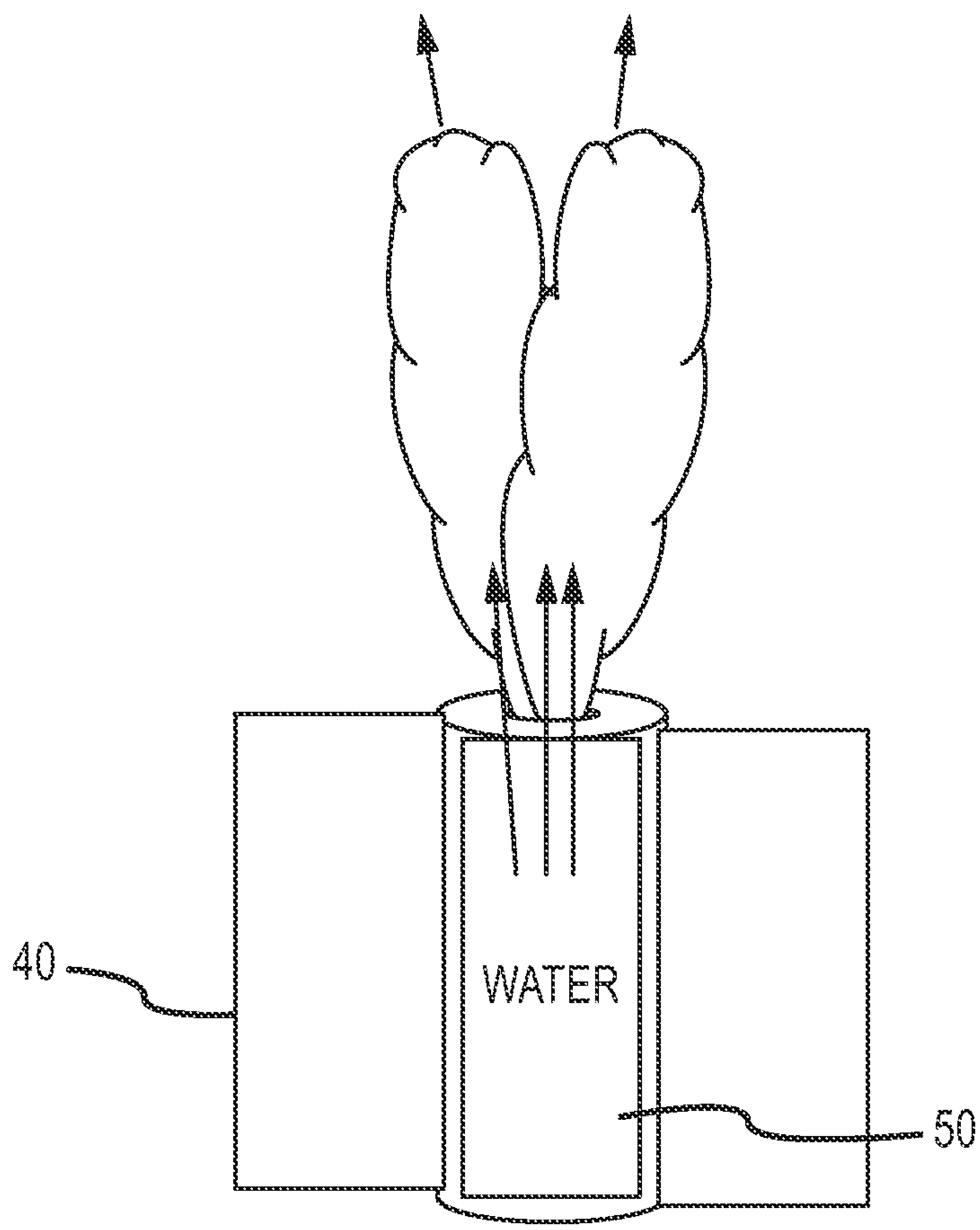

FIG.7

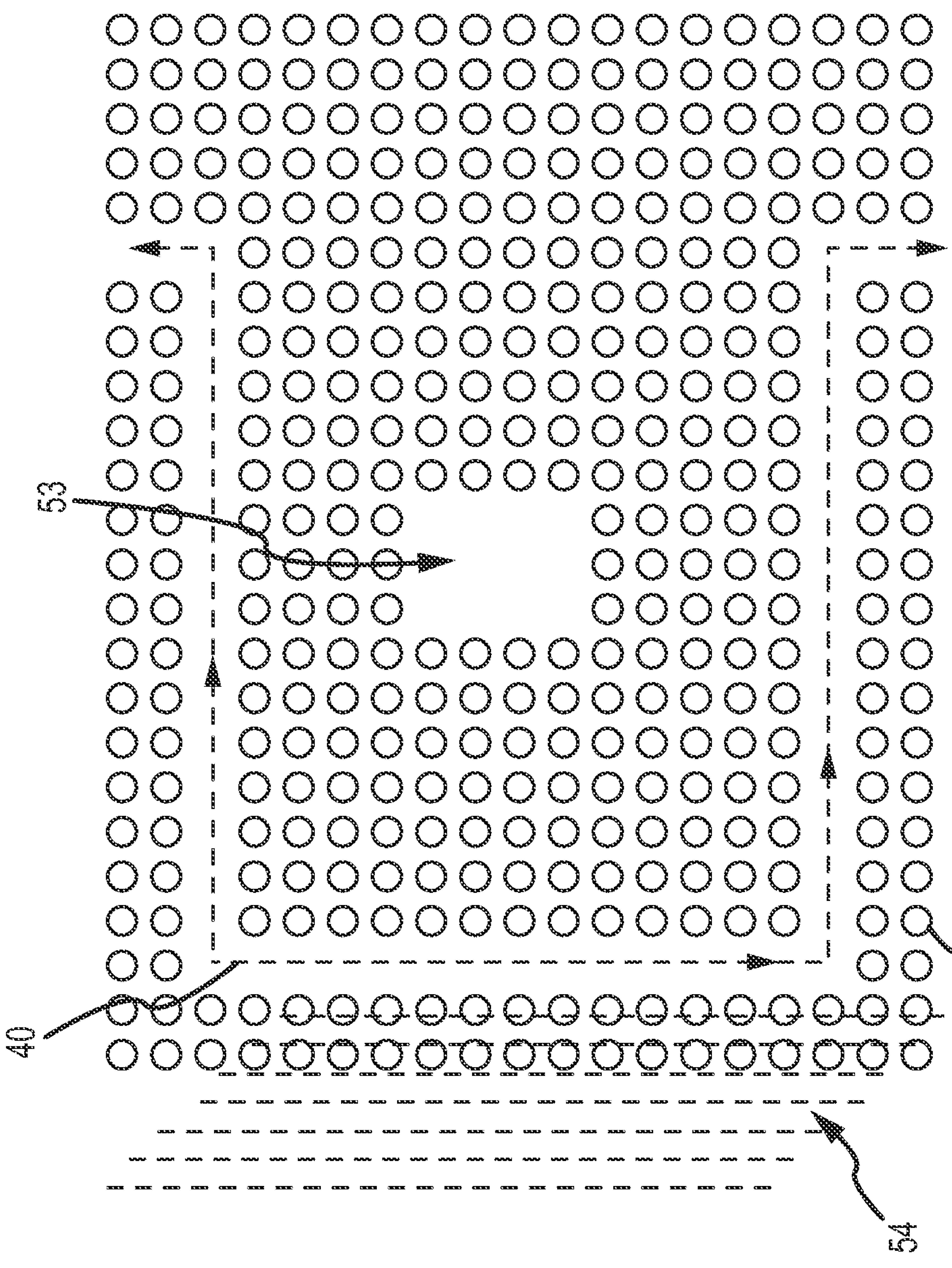

FIG. 8

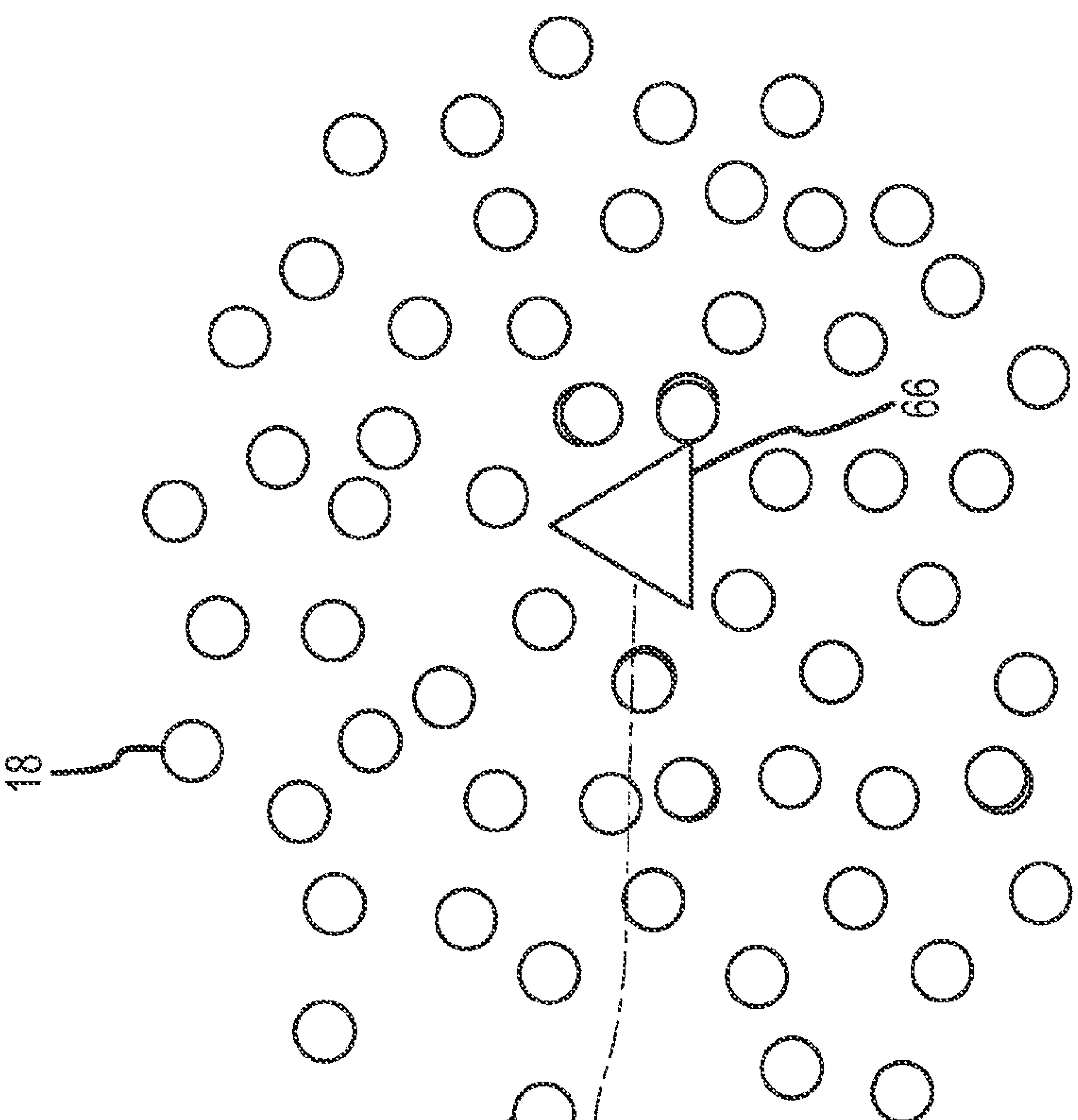

FIG.9b

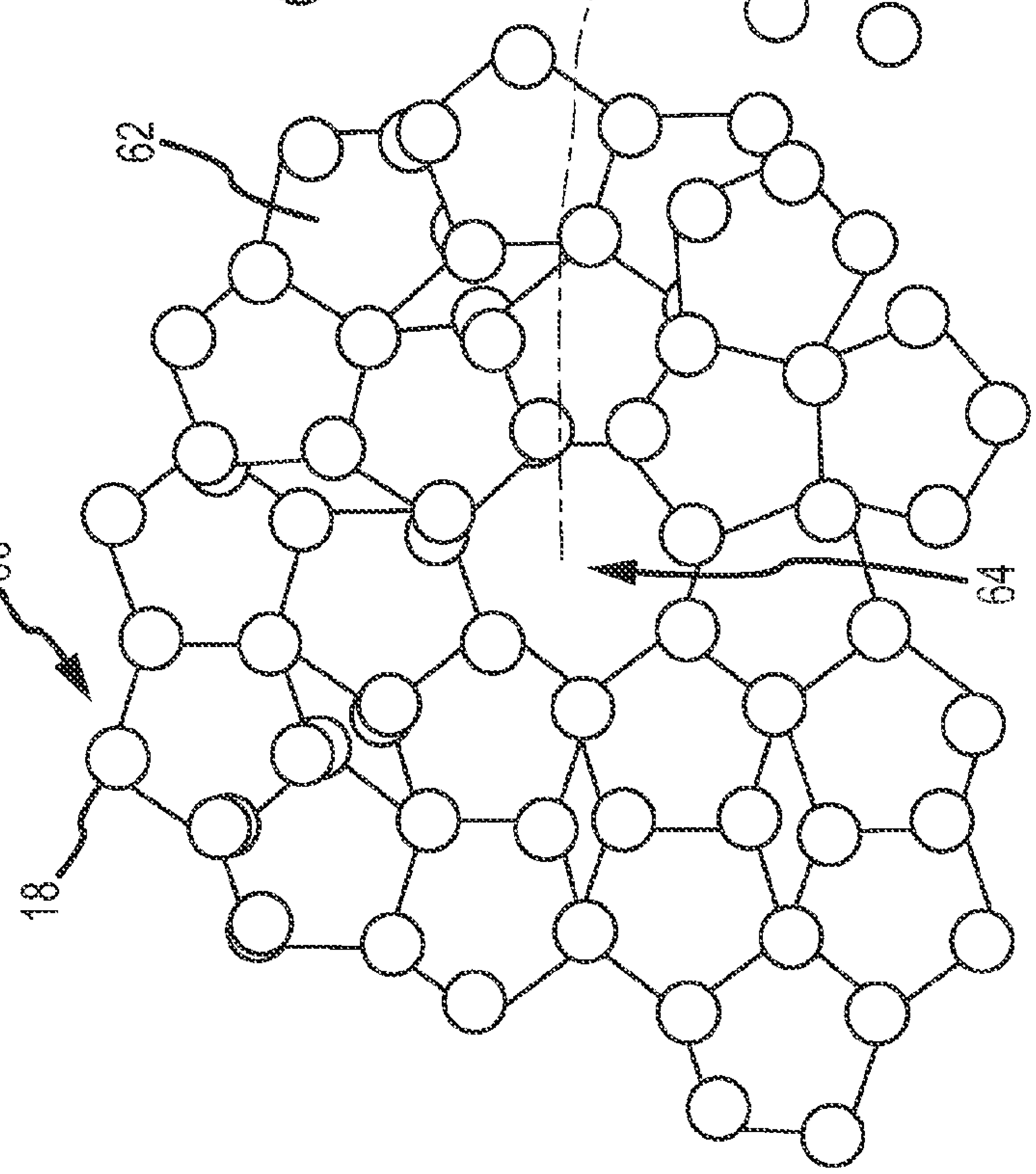

FIG.9a

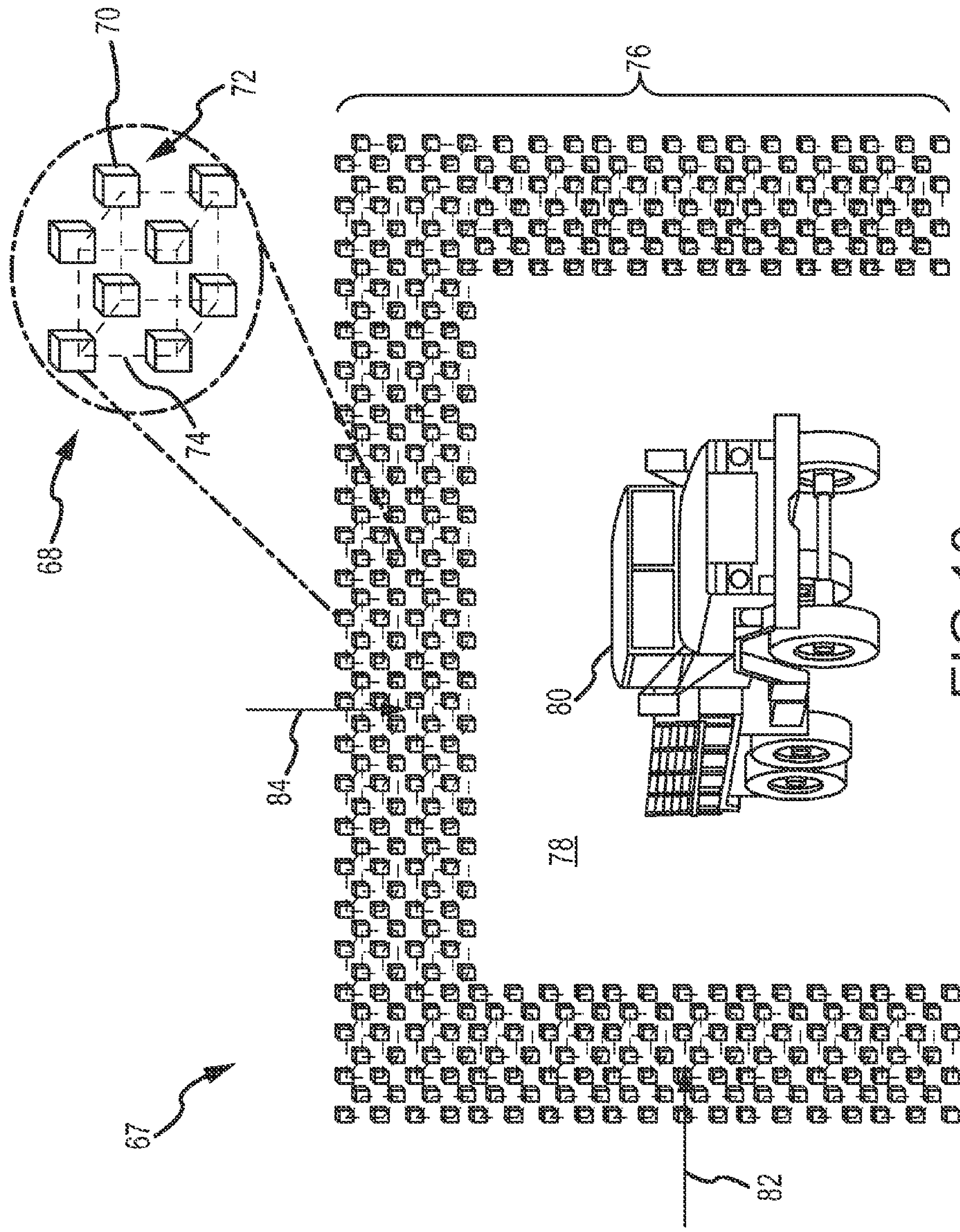

FIG. 10

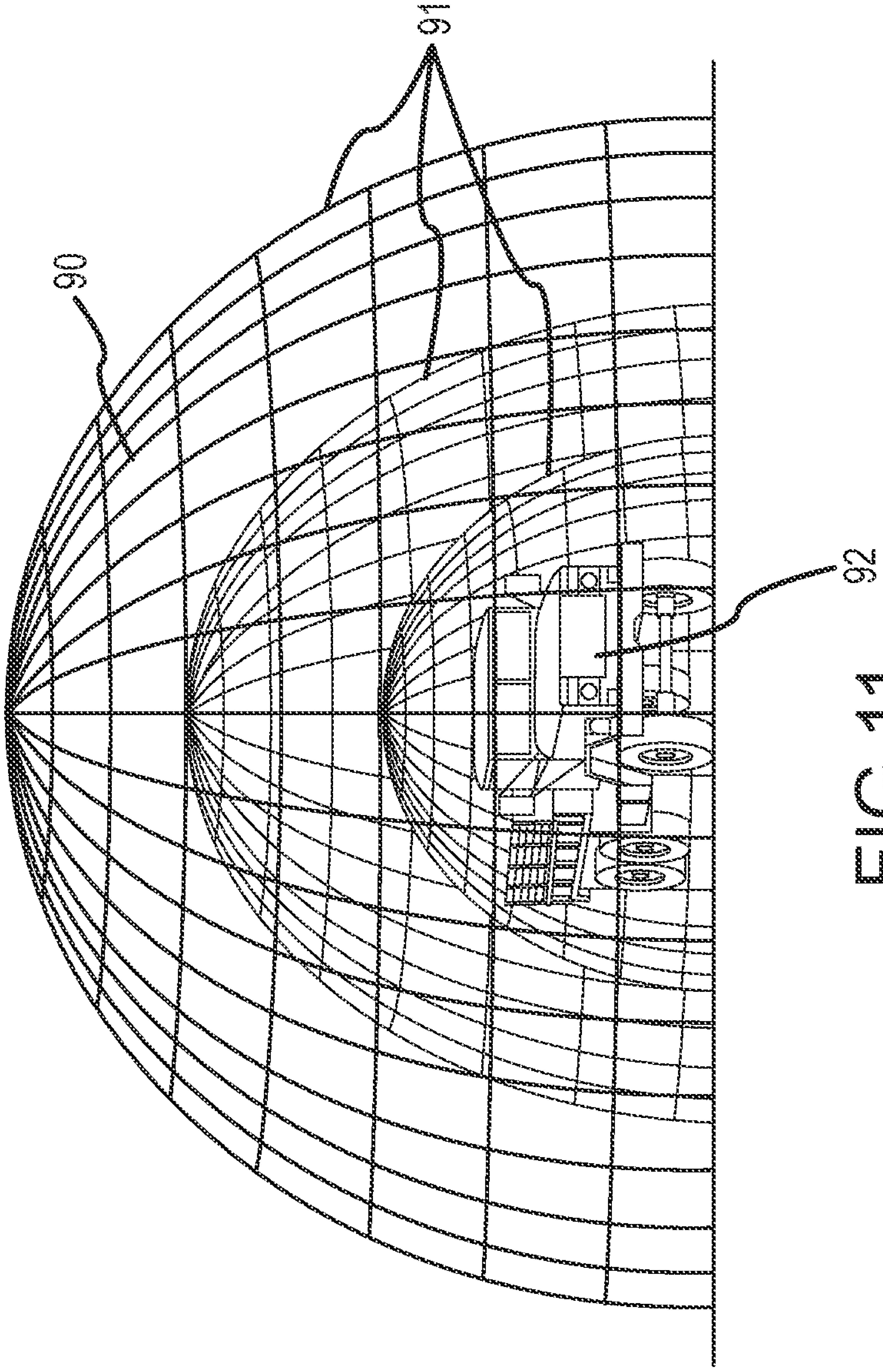

FIG. 11

SHOCK WAVE BARRIER USING MULTIDIMENSIONAL PERIODIC STRUCTURES

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims benefit of priority under 35 U.S.C. 120 as a continuation-in-part of U.S. application Ser. No. 12/473,275 entitled “Acoustic Crystal Explosives” and filed on May 28, 2009 now U.S. Pat. No. 8,082,844, the entire contents of which are incorporated by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to protection of assets in protected areas from shock waves such as produced by explosive detonation.

2. Description of the Related Art

Explosive detonation may produce a shock wave that propagates outwardly from the point of detonation through a media such as air, liquid or a solid. The shock wave is a pressure wave that travels at supersonic speed in the media. The shock wave is characterized by an abrupt, nearly discontinuous change in the characteristics of the medium. Across the shock there is an extremely rapid rise in pressure, temperature and density of the flow. The shock wave carries a large amount of energy in a small volume that can be very destructive. However, the energy of the shock wave dissipates relatively quickly with distance. Furthermore, the accompanying expansion wave approaches and eventually merges with the shock wave, partially cancelling it out. In many explosives, the expansive wave expels metal fragments that provide additional destructive capability.

To protect assets such as buildings or large equipment from the shock waves and fragments resulting from nearby explosive detonations, mass may be placed around the protected area between the asset and an explosive detonation. The mass absorbs the energy in the shock wave through translation of the mass and/or internal friction due to deformation of the mass. Large amounts of mass are required to adequately protect the asset from potential threats. The “mass” may be earth/sand filled plywood walls, earth/sand filled tire walls or vertical reinforced concrete walls. Water filled bladders may be used to absorb the energy in the shock wave and convert it to a vertical spray of water. The mass also provides a barrier to the expelled fragments.

SUMMARY OF THE INVENTION

The following is a summary of the invention in order to provide a basic understanding of some aspects of the invention. This summary is not intended to identify key or critical elements of the invention or to delineate the scope of the invention. Its sole purpose is to present some concepts of the invention in a simplified form as a prelude to the more detailed description and the defining claims that are presented later.

A shock wave barrier comprises a periodic structure having the proper symmetry and local contrast modulation of the acoustic index to divert an incident shock wave by using constructive/destructive interference phenomena that produce a “band gap” in the transmission spectrum of the periodic structure.

In an embodiment, the shock wave barrier comprises first and second media arranged in a periodic structure positioned between a protected area and a potential threat. The first and second media have different acoustic indices of refraction that provide a local contrast modulation of the acoustic index. The symmetry of the periodic structure and local contrast modulation define a band gap in a transmission spectrum of the periodic structure. The first and second media are spaced in the periodic structure to position the band gap coincident with the dominant wavelength of a shock wave produced by the potential threat. The periodic structure is suitably configured such that the band gap spans the dominant wavelengths incident on the structure for a variety of potential threats. The dominant wavelength is a function of the blast pressure of the explosive detonation and the range to the explosive detonation. Generally speaking, the energy of the incident shock wave that lies within the band gap is substantially reflected by the periodic structure.

In an embodiment, the periodic structure is defined by the lattice symmetry of a crystal or quasi-crystal that form band gaps. A crystal lattice exhibits translational symmetry if the structure may be shifted at a certain period and remains identical. The quasi-crystal lattice exhibits rotational symmetry if the structure may be rotated through a certain angle (less than 360 degrees) and remains identical. Rotational symmetry may also provide the added benefit of providing no linear path through the structure thereby enhancing the structure’s capability as a fragment barrier. Translation or rotational symmetry is a necessary but not sufficient condition to produce a band gap. Certain crystal lattices exhibit both translational and rotational symmetry.

In an embodiment, the local contrast modulation of the acoustic indices is equivalent to a velocity contrast in the shock wave incident upon the first few layers of the periodic structure where the wave constructively and destructively interferes. The wavelength at the center of the band gap is approximately equal to or at least on the order of the spacing ‘d’ in the periodic structure. The local contrast modulation largely determines the width of the band gap; the greater the contrast the greater the width. A minimum contrast modulation of approximately 2:1 is needed for a complete band gap. Contrast modulations of 10:1 or greater may be achieved (e.g. steel rods in air or void spaces in concrete) that produce a 50% band gap or greater for acoustic applications. The width of the band gap is typically referenced to its center wavelength.

In an embodiment, the periodic structure comprises a two-dimensional structure that provides local contrast modulation in a two-dimensions. One example is a two-dimensional array of linear elements in air positioned adjacent to or surrounding a protected area. This periodic structure would present a band gap to shock waves travelling along the ground toward the protected area or anywhere in the plane but not perpendicular to the plane of the shock wave. The linear elements could be retracted to provide ingress or egress to the protected area and then deployed to provide the shock wave barrier.

In an embodiment, the periodic structure comprises a three-dimensional structure that provides local contrast modulation in three-dimensions. One example is a concrete hemisphere or box with a periodic array of void three-dimensional objects positioned over the protected area. This structure would present band gaps to shock waves travelling along the ground toward the protected area or shock waves from airborne explosive detonations travelling down towards the protected area.

In an embodiment, one or more defect cavities are formed in the first few layers of the periodic structure in which the constructive/destructive interference occurs. The defect cavity (ies) creates a transmission resonance or “window” in the band gap that allows energy from the shock wave to be collected by the defect cavities. The defect cavity may be detuned to control the width of the window. The collected energy may be dissipated in the defect cavities by, for example, expelling a material such as water or sand that fills the cavity. The collected energy may be rerouted through the periodic structure around the protected area via a waveguide formed by a pattern of defect cavities.

These and other features and advantages of the invention will be apparent to those skilled in the art from the following detailed description of preferred embodiments, taken together with the accompanying drawings, in which:

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. **1***a* and **1***b* are planar and perspective views of an embodiment of a shock wave barrier comprising a periodic structure of metal rods in air surrounding a protected area;

FIG. **2** is a plot of the barrier's transmission profile exhibiting a band gap;

FIGS. **3***a* and **3***b* are plots of a shock wave and its response at the barrier coincident with the band gap;

FIGS. **4***a* and **4***b* are planar and perspective views of the shock wave barrier illustrating the constructive/destructive interference that occurs in the first few layers of the periodic structure to form the band gap and reflect the energy of the shock wave;

FIG. **5** is a planar view of an embodiment of a shock wave barrier comprising defect cavities formed in the periodic structure that form a resonance in the band gap to collect energy from the shock wave;

FIG. **6** is a plot of the barrier's transmission profile exhibiting a defect resonance within the band gap;

FIG. **7** is a diagram of a water filled defect cavity configured to dissipate the collected energy by expelling the water from the cavity;

FIG. **8** is a plan view of a periodic structure including multiple defect cavities that form a waveguide to collect and reroute the transmitted energy away from the protected area;

FIGS. **9***a* and **9***b* are diagrams of a periodic structure that exhibits rotational symmetry;

FIG. **10** is a diagram of an embodiment of a three-dimensional periodic structure comprising void spheres arranged in a concrete hemisphere; and

FIG. **11** is a diagram of an embodiment of a three-dimensional periodic structure comprising concentric hemispheric mesh structures arranged in air.

DETAILED DESCRIPTION OF THE INVENTION

The present invention describes a shock wave barrier. This is accomplished with a periodic structure having the proper symmetry and local contrast modulation of the acoustic index to divert an incident shock wave by using the constructive/destructive interference phenomena that produces a "band gap" in the transmission spectrum of the periodic structure. In general, shock wave energy at wavelengths within the band gap is reflected from the structure. Defect cavities may be formed in the periodic structure to create transmission resonances or "windows" in the band gap. A portion of the incident energy passes through the window and is concentrated in the defect cavities where it is dissipated by other means. The band gap can be quite wide, at least 50% of the center wavelength, and thus can provide an effective barrier from a wide variety of threats with varying blast pressure and range. The structure may be periodic in two or three dimensions providing a band gap barrier in two or three dimensions, respectively.

Referring now to FIGS. **1***a*-**1***b* and **2**, in an embodiment a shock wave barrier **10** comprises a first media of linear elements (e.g. rods) **12** and a second media of air **14** arranged in a periodic structure **16** of multiple layers **18** around a protected area **20** and asset **22**. The first and second media have different acoustic indices of refraction that provide a local contrast modulation of the acoustic index orthogonal to the linear elements and the periodic structure. The symmetry of the periodic structure and local contrast modulation define a band gap **24** in a transmission spectrum **26** of the periodic structure. Incident energy that falls within the band gap **24** is reflected from the periodic structure. The periodic structure is suitably configured such that the band gap **24** spans the dominant wavelengths incident on the structure for a variety of potential threats (e.g. varying blast pressures at varying distances to the protected area). In some embodiments, the rods **12** may be retractable to allow ingress or egress to the protected asset or of the protected asset.

Periodic structure **16** is configured to produce constructive/destructive interference of an incident shock wave to define band gap **24**. The symmetry, local contrast modulation, number of layers and spacing of the periodic structure form band gap **24** and determine its center wavelength, width and definition.

Periodic structure **16** exhibits a symmetry that will form a band gap. There are many crystal and quasi-crystal lattices that are known to form band gaps in crystalline periodic structures. To form periodic structure **16** the first media (rods) **12** are arranged in a pattern corresponding to the vertices of the crystal or quasi-crystal lattice within the second media (air) **14**. In this particular embodiment, the periodic structure is based on a square crystal lattice. Other patterns based on, for example, a triangular or honeycomb crystal lattice may be used.

A crystal lattice exhibits translational symmetry if the structure can be translated by a certain distance and remains identical. The quasi-crystal lattice exhibits rotational symmetry if the structure may be rotated through a certain angle (less than 360 degrees) and remains identical. Rotational symmetry may also provide the added benefit of providing no linear path through the structure thereby enhancing the structure's capability as a fragment barrier. Certain crystal lattices exhibit both translational and rotational symmetry. Translation or rotational symmetry is a necessary but not sufficient condition to produce a band gap. To date, no general solution has been identified to specify all types of crystals and quasi-crystals that will form band gaps.

Periodic structure **16** exhibit a minimum local contrast modulation of the acoustic index of approximately 2:1 to form a complete band gap. This modulation produces a velocity contrast in the shock wave incident upon the first layers of the periodic structure where the wave constructively and destructively interferes. Contrast modulations of 10:1 or greater may be achieved (e.g. steel rods in air or void spaces (air) in concrete) that produce a 50% band gap or greater. The width of the band gap is typically referenced to its center wavelength.

The 'acoustic index' of refraction is defined as the ratio of the speed of sound in a control medium to the speed of sound in the material of interest. We have selected diamond as the control medium although any medium can be used. When computing the contrast or local modulation of the acoustic index the control medium cancels out leaving only the properties of the first and second media. Table 1 lists a number of different media, the speed of sound in the material and acoustic indices. The Table is not an exhaustive list of usable media, merely representative. As shown a combination of metal and air produces modulations in excessive of 10:1.

TABLE 1

Material	m/sec	Acoustic Index
Diamond	12000	1.00
Air (STP)	343	35
Aluminum	4877	2.46
Brass	3475	3.45
Copper	3901	3.08
Iron	5130	3.08
Lead	1158	10.36
Steel	6100	1.97
Water	1433	8.37
Concrete	3200-3600	3.33-3.75
Brick	4176	2.87

Periodic structure **16** includes multiple layers **18** to adequately establish and define band gap **24**. As shown in FIG. **2**, the definition of band gap **24** improves with additional layers. Typically, a periodic structure comprising 6-10 layers **18** provide a well-defined band gap **24** with approximately zero transmission across the band gap.

The wavelength at the center of the band gap is approximately equal to or at least on the order of the spacing 'd' in periodic structure **16**. Secondary factors such as element diameter, element shape and small positional placement of the elements that are slightly symmetry braking will contribute to the exact spacing 'd' required for a specific center wavelength.

In an embodiment, periodic structure **18** may be actively controlled to open or close the band gap, or shift the edges of the band gap. The periodic structure may be actively controlled by modulating the contrast of the acoustic indices, changing the geometric arrangement or altering the symmetry.

Referring now to FIGS. **3***a*-**3***b* and **4***a*-**4***b*, an explosive detonation **30** produces a shock wave **32**. Shock wave **32** travels as a plane wave at supersonic speed in air towards periodic structure **16** and protected area **20** and asset **22**. The shock wave is characterized by an abrupt, nearly discontinuous change in the air pressure.

Simplifying, the blast pressure produced by the explosive detonation forms the initial shock wave. The response **34** of the shock wave as it arrives at the barrier may be characterized by a dominant wavelength **36**. Most of the energy in the shock wave is centered about the dominant wavelength. This wavelength is to a large extent determined by the amount and type of explosive. As the shock wave propagates through air towards the protected area and decays its dominant wavelength shifts downwards. Consequently, the dominant wavelength incident on the periodic structure is determined by the initial blast pressure and the range. Depending upon the application (protected area and asset) and the potential threats (initial blast pressures and ranges), the periodic structure is configured to present a band gap that spans the dominant wavelengths of the incident shock wave for a variety of potential threats. The band gap is also positioned to reflect those wavelengths that most efficiently and destructively couple to the asset.

When shock wave **32** reaches periodic structure **16** energy within band gap **24** will constructively and destructively interfere and be substantially reflected away from the structure as reflected energy **37** while energy outside the band gap will be transmitted through the structure. The incident shock wave interacts with the rods in the periodic structure to produce secondary waves **38**. These secondary waves intersect and produce destructive interference and cancellation of a wide band of wavelengths to form the band gap. The energy outside the band gap is naturally attenuated or does not couple destructively to the asset.

In certain situations it may not be desirable to reflect all or even a substantial portion of the shock wave. The reflection may cause collatoral damage of other nearby assets. As shown in FIG. **5**, defect cavities **40** may be formed in the first few layers of periodic structure **16**. The defect cavity may be any significant disturbance or "defect" in the periodic structure e.g. the absence of one or more rods **18** or different geometry of the one or more rods **18**. Defect cavities **40** create a transmission resonance **42** or "window" in band gap **24** as shown in FIG. **5**. The defect cavity may be detuned to control the width of the transmission resonance. The defect cavity may be detuned by altering the size of the defect, the acoustic index of refraction or the lattice constant of the periodic structure. A portion of the incident energy passes through the window and is concentrated in the defect cavities where it is dissipated by other means.

As shown in FIG. **7**, an embodiment to dissipate the energy concentrated in the defect cavities is to fill the cavities **40** with another media **50** such as water or sand. The energy is dissipating by ejecting media **50** from the defect cavity.

As shown in FIG. **8**, another embodiment to dissipate the energy is to configure the defect cavities **40** to form a waveguide **52** to reroute the energy around and away from a protected area **53**. The energy from an incident plane wave **54** is collected by the defect cavities **40** and routed through waveguide **52** around protected area **53**.

As shown in FIG. **9**, rods **18** may be positioned at the vertices **60** of a quasi-crystal lattice **62** around a protected area **64** and asset **66**. The pattern of rods **18** exhibits a rotational symmetry that forms a band gap. A benefit of this pattern is that it provides no clear linear path from the outside through the periodic structure to the protected area. This increases the periodic structure's viability as a fragment barrier in addition to being a shock wave barrier.

The periodic structure may comprise a three-dimensional structure that provides local contrast modulation in two dimensions. This structure comprises three-dimensional objects (spheres, cubes, rods, etc.) arranged with certain symmetry in a contrasting media that form a band gap.

Referring now to FIG. **10**, in an embodiment of a three-dimensional shock wave barrier **67** a unit cell **68** of the periodic structure comprises cubes **70** arranged at the vertices **72** of a cubic lattice **74**. Unit cells **68** are repeated in a three-dimensional periodic structure **76** both around and above a protected area **78** and asset **80**. The structure provides local contrast modulation in a first dimension **82** orthogonal to its walls and a second dimension **84** orthogonal to the ceiling. As such, shock wave energy from either a terrestrial or airborne explosive detonation may be reflected. In an alternate embodiment, the unit cells **68** may be repeated in a hemispheric configuration around and above protected area **78**. In one example, cubes **70** are void spaces of air embedded in a concrete media. Alternately, cubes **70** may be metal objects suspended in a lattice in air.

Referring now to FIG. **11**, in an embodiment of a three-dimensional shock wave barrier **89** comprises unit cells **90** constructed from welded circular elements of a suitable material such as steel. The three-dimensional periodic structure is formed of concentric hemispheres **91** of unit cells **90** with the appropriate spacing. The band gap is obtained by arranging smaller concentric hemisphere structures with the appropriate spacing between hemisphere radii. A protected asset **92** sits at the center of the structure that contains at least 6 concentric hemispheres. A door structure may be provided thru the hemispheres for ingress and egress.

As described above, the shock wave barrier may be configured to protect an area and an asset from shock waves travelling in air. The barrier may be configured to protect an area and an assets from shock waved travelling in liquid (e.g. the ocean), in solids (e.g. tank armor) or through the ground towards an underground area. The dominant wavelengths of the shock wave will change, hence the spacing of the periodic structure will change to position a band gap coincident with the dominant wavelength but the principle remains the same.

While several illustrative embodiments of the invention have been shown and described, numerous variations and alternate embodiments will occur to those skilled in the art. Such variations and alternate embodiments are contemplated, and can be made without departing from the spirit and scope of the invention as defined in the appended claims.

We claim:

1. A shock wave barrier for an asset in a protected area, comprising:

first and second media arranged in a multidimensional periodic structure having a symmetry, said structure positioned between the protected area and one or more potential explosive detonation threats, said first and second media having different acoustic indices of refraction that provide a local contrast modulation of the acoustic index that in conjunction with the symmetry of the structure defines a band gap in a transmission spectrum of the periodic structure, said first and second media spaced in the periodic structure to position the band gap coincident with the dominant wavelength of the shock wave for one or more potential explosive detonation threats.

2. The shock wave barrier of claim **1**, wherein the periodic structure reflects show shock wave energy at wavelengths within the band gap.

3. The shock wave barrier of claim **1**, wherein the periodic structure exhibits translational or rotational symmetry.

4. The shock wave barrier of claim **1**, wherein the local contrast modulation of the acoustic index is at least 2:1.

5. The shock wave barrier of claim **1**, wherein the periodic structure comprises at least six layers within which the shock wave constructively and destructively interferes to form the band gap.

6. The shock wave barrier of claim **1**, wherein the first media comprises air.

7. The shock wave barrier of claim **6**, wherein the local contrast modulation of the acoustic index is at least 10:1 and the width of the band gap is at least 50% of the center wavelength of the band gap.

8. The shock wave barrier of claim **1**, wherein said first media comprises linear elements that provide local contrast modulation in two dimensions, said linear elements arranged in said second media in a three-dimensional periodic structure that define the local contrast modulation and band gap approximately in two dimensions.

9. The shock wave barrier of claim **8**, wherein the linear elements may be retracted to permit ingress and egress from the protected area.

10. The shock wave barrier of claim **1**, wherein said first media comprises three-dimensional geometric objects that provide local contrast modulation in three dimensions, said three-dimensional objects arranged in said second media in a three-dimensional periodic structure that defines the local contrast modulation and band gap in three dimensions.

11. The shock wave barrier of claim **1**, further comprising:

one or more defect cavities in the periodic structure that create a transmission resonance with the band gap that allows energy from the shock wave to pass into the structure where it is concentrated within the one or more defect cavities.

12. The shock wave barrier of claim **11**, wherein the one or more defect cavities are filled with a third media that is ejected from the cavity to dissipate the energy.

13. The shock wave barrier of claim **11**, wherein a plurality of said defect cavities forms a waveguide that routes the energy away from the protected area.

14. A shock wave barrier for an asset in a protected area, comprising:

linear elements arranged in air around a protected area in a three-dimensional periodic structure that exhibits translational or rotational symmetry, said linear elements having an acoustic index of refraction of at most one-tenth that of air to provide a local contrast modulation of the acoustic index in two-dimensions of at least 10:1 that in conjunction with the symmetry of the structure defines a band gap in a transmission spectrum of the periodic structure, said linear elements spaced in the periodic structure to position the band gap coincident with the dominant wavelength of the shock wave for one or more potential explosive detonation threats, said band gap having a width of at least 50% of its center wavelength.

15. The shock wave barrier of claim **14**, wherein the periodic structure reflects shock wave energy at wavelengths within the band gap.

16. The shock wave barrier of claim **14**, further comprising:

one or more defect cavities in the periodic structure that create a transmission resonance within the band gap that allows energy from the shock wave to pass into the structure where it is concentrated within the one or more defect cavities; and

means for dissipating the energy in the one or more defect cavities.

17. The shock wave barrier of claim **14**, wherein the linear elements may be retracted to permit ingress and egress from the protected area.

18. A shock wave barrier for an asset in a protected area, comprising:

first and second media arranged in a multidimensional periodic structure having a symmetry, said structure positioned between the protected area and one or more potential explosive detonation threats, said first and second media having different acoustic indices of refraction that provide a local contrast modulation of the acoustic index that in conjunction with the symmetry of the structure defines a band gap in a transmission spectrum of the periodic structure, said first and second media spaced in the periodic structure to position the band gap coincident with the dominant wavelength of the shock wave for one or more potential explosive detonation threats;

one or more defect cavities in the periodic structure that create a transmission resonance with the band gap that allows energy from the shock wave to pass into the structure where the energy is concentrated within the one or more defect cavities; and

means for dissipating the energy in the one or more defect cavities.

19. The shock wave barrier of claim **18**, wherein the means for dissipating the energy comprises a third media in the one or more defect cavities that is ejected from the cavity to dissipate the energy.

20. The shock wave barrier of claim **18**, wherein the means for dissipating the energy comprises a waveguide formed by a plurality of said defect cavities that routes the energy away from the protected area.

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